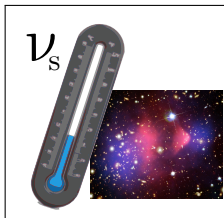


Sterile neutrinos as thermal dark matter

Rasmus S. L. Hansen
Max-Planck-Institut für Kernphysik, Heidelberg

based on work in collaboration with
Stefan Vogl (arXiv:1706.02707)

WIN 2017, Irvine
June 20



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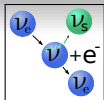
keV sterile neutrino dark matter

- Dark matter is present - its nature is unknown.
- SM neutrinos, ν_a , are too light/hot to be good dark matter candidates.
- ν_a could still have a small mixing with heavier SM singlets - sterile neutrinos, ν_s .
- The most interesting mass range is $\sim 3 - 100\text{keV}$.
- Production mechanisms:
 - Oscillations - with and without a resonance
 - Decay production
 - Thermal production and dilution



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Production through oscillations

Boltzmann equation

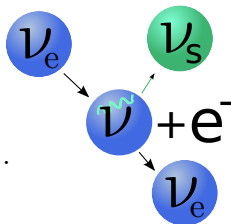
$$\frac{\partial}{\partial t} f_{\nu_s} - H p \frac{\partial}{\partial p} f_{\nu_s} \approx \gamma (f_{\nu_a} - f_{\nu_s}),$$

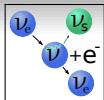
$$\gamma = \frac{1}{4} \frac{\Gamma_a \Delta^2 \sin^2 2\theta}{\Delta^2 \sin^2 2\theta + \frac{\Gamma_a^2}{4} + [\Delta \cos 2\theta - V_T - V_L]^2}.$$

Γ_a - collision rate.

$\Delta^2 \approx \frac{m_{\nu_s}^2}{2p}$ - mass squared difference.

$V_T \propto \rho_e$, $V_L \propto n_{\nu_e} - n_{\bar{\nu}_e}$ - thermal potentials.



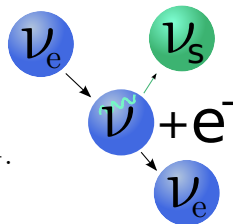


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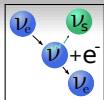
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Absence of resonance (DW) in $\Delta \cos 2\theta - V_T - V_L$ gives $f_{\nu_s} \sim \frac{1}{\Lambda} f_{\nu_a}$.

Dodelson and Widrow (hep-ph/9303287)

Deviations due to entropy production during production are non-negligible. Abazajian (astro-ph/0511630), Merle, Schneider and Totzauer (1512.05369)

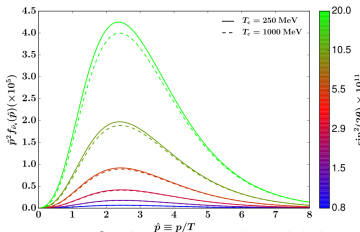
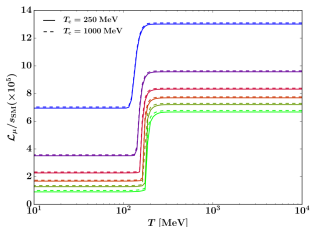
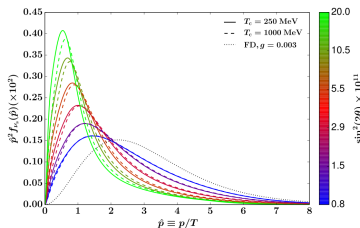
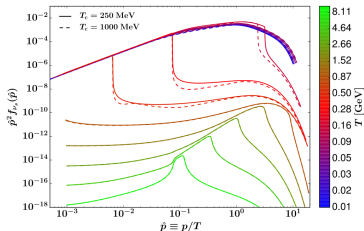


Production through oscillations

Resonant production Shi, Fuller (astro-ph/9810076)

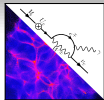
Lepton asymmetry \gg baryon asymmetry $\Rightarrow V_L \sim \Delta \cos 2\theta$.

Enhanced production and smaller mixing angles can produce Ω_{DM} .

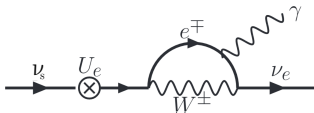


Venumadhav, Abazajian and Hirata (1507.06655)

Sterile neutrinos as thermal dark matter

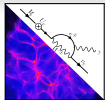


X-rays from sterile neutrinos

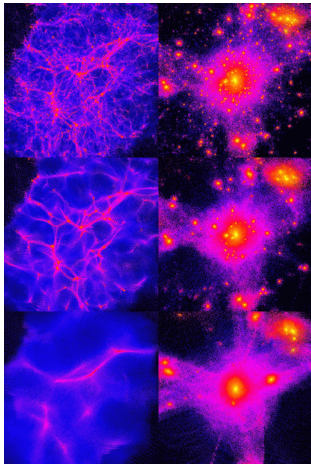


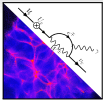
- Monoenergetic line.
- Signal regions: Galactic center, M31 (Andromeda), Galaxy clusters, Dwarf galaxies, diffuse background.

$$\Gamma \propto \sin^2 2\theta m_{\nu_s}^5$$

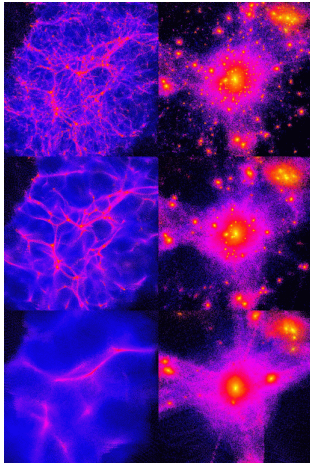


Structure formation and the Lyman- α forest



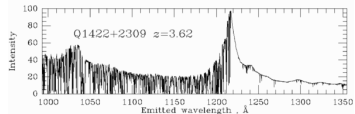
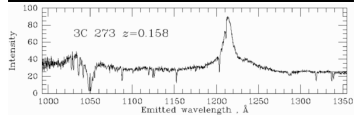
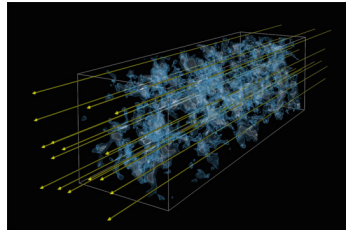


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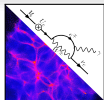


ITP, University of Zurich

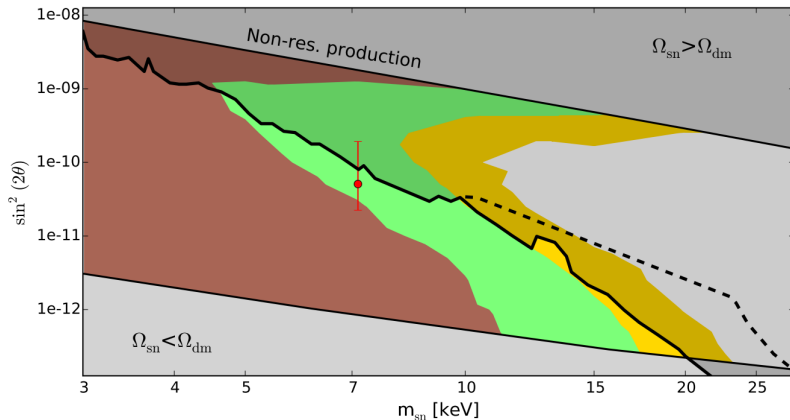
Khee-Gan Lee (MPIA) and Casey Stark (UC Berkeley)



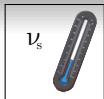
Bill Keel



Constraints on ν_s produced through oscillations



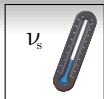
Schneider (1601.07553)



Thermalization

Goal:

- Lower average momentum.
- Enhanced number density.



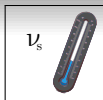
Thermalization

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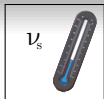
Prerequisites:

- Coupling to a new boson φ with $m_{\nu_s} \ll m_\varphi \ll T_{\nu_s, \text{production}}$.
- Efficient number changing processes for φ .



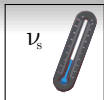
Thermalization - General mechanism

- I **$T \sim 100\text{MeV}$** : ν_s and $\bar{\nu}_s$ are produced out-of-chemical equilibrium via oscillations.
- II **$T \sim 100 - 10\text{MeV}$** : ν_s and $\bar{\nu}_s$ interact and produce φ . φ reaches chemical equilibrium via a rapid number changing processes.
- III **$T \sim 10 - 1\text{MeV}$** : Once a sufficient abundance of φ has been built up, the production of ν_s and $\bar{\nu}_s$ from φ becomes efficient and ν_s and $\bar{\nu}_s$ are also driven towards chemical equilibrium.
- IV **$T \sim 1\text{MeV}$** : The φ particles becomes non-relativistic and annihilate or decay to $\nu_s\bar{\nu}_s$.



Thermalization - General mechanism

| **$T \sim 100\text{MeV}$** : In DW $f_{\nu_s} \approx \frac{1}{\Lambda} f_{\nu_a}$, typically $\Lambda \sim 10^4 - 10^6$.

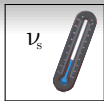


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II-III **$T \sim 100 - 1\text{MeV}$** : $\rho \propto a^{-4}$ during equilibration. ($s \cdot a^3$ grows)

$$\rho_{\nu_s, \text{initial}}(a_i) a_i^4 = \rho_{s, \text{eq}}(a_\varphi) a_\varphi^4 \quad \Rightarrow \quad T_\varphi = \left(\frac{2}{2 + \frac{8}{7} g_\varphi} \right)^{1/4} \Lambda^{-1/4} T_\gamma,$$



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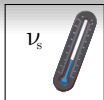
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IV **$T \sim 1\text{MeV}$** : φ transfers entropy to ν_s :

$$s(a_\varphi) a_\varphi^3 = s(a_f) a_f^3 \quad \Rightarrow \quad T_f = \left(1 + \frac{4}{7} g_\varphi \right)^{1/12} \Lambda^{-1/4} T_\gamma.$$

Final number density:

$$\frac{n_{\nu_s, f}}{s_{\text{SM}}} = \left(1 + \frac{4}{7} g_\varphi \right)^{1/4} \Lambda^{1/4} \frac{n_{\nu_s, i}}{s_{\text{SM}}}$$



Toy model

Scalar boson φ coupled to ν_s :

$$\mathcal{L} = \frac{1}{2} \partial^\mu \varphi \partial_\mu \varphi - \frac{1}{2} m_\varphi^2 \varphi^2 - \frac{\lambda}{4} \varphi^4 + y \bar{\nu}_s \nu_s \varphi$$

We assume no coupling to Higgs.

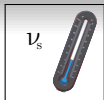
e.g. Heikinheimo et al. (1604.02401 and 1704.05359) discuss a Higgs coupling

Decay width:

$$\Gamma_\varphi \approx \frac{1}{4\pi} y^2 m_\varphi ,$$

Number changing interactions:

$$\sigma \nu_{2 \rightarrow 4} \approx \frac{27\sqrt{3}}{64\pi^4} \frac{\lambda^4 T^3}{m_\varphi^5} \exp\left(-\frac{2m_\varphi}{T}\right) .$$



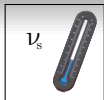
Constraints on the coupling

- Assume that the new interaction has no influence on the production through oscillations.
- Two main effects from the new interaction:
 - The potential from a sterile lepton asymmetry

$$V_{s, \text{asym}} = \frac{y^2}{2m_\varphi^2} \Delta n_{\nu_s}.$$

- Inverse decays \rightarrow increased collision rate

$$\Gamma_{\nu_s} \approx \frac{m_\varphi^2 \Gamma_\varphi T_\varphi}{8\pi^2} \frac{K_1\left(\frac{m_\varphi}{T_\varphi}\right)}{n_{\nu_s}},$$

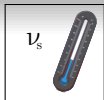


Constraints on the coupling

- $V_{s, \text{asym}}$ is only relevant for resonant production.
Require $V_L > 10V_{s, \text{asym}}$. Strongest at final values.

$$y < 2 \times 10^{-8}, \quad y < 1 \times 10^{-7} \quad \text{and} \quad y < 1 \times 10^{-6},$$

for $m_{\nu_s} = 3, 7$ and 50keV and $m_\varphi = 100, 100$ and 200keV .



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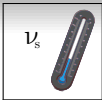
for $m_{\nu_s} = 3, 7$ and 50keV and $m_\varphi = 100, 100$ and 200keV.

- The inverse decay rate result in a production of ν_s at the rate $\Gamma_{\text{ID}} = \frac{1}{4} \sin^2 2\theta \Gamma_{\nu_s}$ and is maximal at $T \sim m_\varphi$.

Require $\Gamma_{\text{DW}}(T_{\gamma, \text{DW}})/H(T_{\gamma, \text{DW}}) > 10 \Gamma_{\text{ID}}(T_{\varphi, \text{ID}})/H(T_{\gamma, \text{ID}})$.

$$y < 2 \times 10^{-7}, \quad y < 4 \times 10^{-7} \quad \text{and} \quad y < 3 \times 10^{-6},$$

for $m_{\nu_s} = 3, 7$ and 50keV and $m_\varphi = 100, 100$ and 200keV.



Momentum averaged treatment

Integrated Boltzmann equations:

$$\dot{\rho}_\varphi + CH\rho_\varphi = \Gamma_{\rho\nu_s}\rho_{\nu_s} + \Gamma_{\rho\bar{\nu}_s}\rho_{\bar{\nu}_s} - \Gamma_{\rho\varphi}\rho_\varphi ,$$

$$\dot{\rho}_{\nu_s} + 4H\rho_{\nu_s} = \Gamma_{\rho\varphi}\rho_\varphi/2 - \Gamma_{\rho\nu_s}\rho_{\nu_s} ,$$

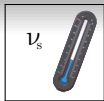
$$\dot{\rho}_{\bar{\nu}_s} + 4H\rho_{\bar{\nu}_s} = \Gamma_{\rho\varphi}\rho_\varphi/2 - \Gamma_{\rho\bar{\nu}_s}\rho_{\bar{\nu}_s} ,$$

$$\dot{n}_{\nu_s} + 3Hn_{\nu_s} = \Gamma_{n\varphi}n_\varphi - \Gamma_{n\nu_s}n_{\nu_s} ,$$

$$\dot{n}_{\bar{\nu}_s} + 3Hn_{\bar{\nu}_s} = \Gamma_{n\varphi}n_\varphi - \Gamma_{n\bar{\nu}_s}n_{\bar{\nu}_s} ,$$

$$\Gamma_{n\varphi} = \frac{3}{2}\Gamma_{\rho\varphi} = \frac{1}{2}\frac{m_\varphi}{T_\varphi}\Gamma_\varphi , \quad \Gamma_{n\nu_s} = 3\Gamma_{\rho\nu_s} = \frac{1}{4}\frac{m_\varphi T_{\bar{\nu}_s}}{T_{\nu_s}^2} \exp\left[\frac{\mu_{\bar{\nu}_s}}{T_{\bar{\nu}_s}}\right] \Gamma_\varphi .$$

$$C = \frac{1}{2\pi^2\rho_\varphi} \int dp (p^4 E^{-1} + 3p^2 E) f_\varphi(p, t),$$



Momentum averaged treatment

Benchmark:

$$m_{\nu_s} = 7\text{keV},$$

$$m_\varphi = 0.1\text{MeV},$$

$$\frac{n_{\bar{\nu}_s}}{n_{\nu_s}} = 3 \times 10^{-2}$$

$$\text{and } y = 7 \times 10^{-9}.$$

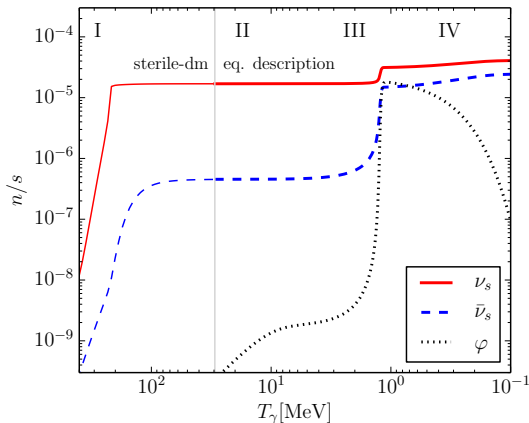
In general:

$$y > 6 \times 10^{-9}$$

$$\text{for } m_{\nu_s} \lesssim 7\text{keV}$$

$$y > 2 \times 10^{-8}$$

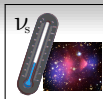
$$\text{for } m_{\nu_s} \gtrsim 50\text{keV}$$



sterile-dm

Venumadhav, Abazajian and Hirata (1507.06655)

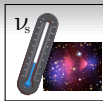




Summary and conclusions

- The thermalization of sterile neutrinos in a dark sector can be achieved in very simple models.
- The process rely on a coupling of the sterile neutrino to other particles in the dark sector and efficient number changing processes in that sector.
- Thermalization results in significantly weaker bounds from structure formation and allow lower values of $\sin^2 2\theta$ to produce sterile neutrino dark matter resonantly.
- The parameter space for production through oscillations is enlarged.

Thanks for your attention!



Mixing parameter grid

